# Next Generation Weather Radar Program

## Radar Operations Center

## "On Measuring WSR-88D Antenna Gain Using Solar Flux"

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On Measuring WSR-88D Antenna Gain Using Solar Flux

By

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*Abstract*

*Examination of the various factors involved indicates that the WSR-88D antenna gain radome loss and received signal microwave loss can be estimated to an accuracy of 0.44 dB using solar flux. Although an accuracy of 0.2 dB in antenna gain is attainable on a carefully controlled and instrumented radar range, the gain measured by the solar flux method has the advantage of being the composite of everything from the outside world to the receiver calibration port in operational cascade, being traceable to an absolute standard, and is verifiable without use of unrepeatable historical data.*

*The solar flux gain accuracy of 0.44 dB results in a rainfall accuracy of ±8% for a reflectivity rainfall relationship of* $Z = 300\,R^{1.4}$

On Measuring WSR-88D Antenna Gain Using Solar Flux

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## 1. Introduction

Solar flux density measurements are utilized routinely for antenna pointing accuracy verification and have also been examined for antenna gain checks for some time [Andrews, 1969; Pratt and Ferraro, 1989; and Tapping, 1994]. However, it is only recently that the accuracy of the flux measurements reported by the observatories became sufficiently quantitative for comparison with antenna range measurements of antenna gain. The use of solar flux for antenna gain verification is appealing for the WSR-88D network calibration maintenance because of its network wide applicability and relative ease of execution compared to antenna range or known target gain verification.

The purpose of this paper is to examine the potential of using the solar flux for antenna gain measurement with the present state of the art. This is done by presenting the theory of gain measurement, characteristics of the solar flux, description of the solar flux routine, and receiver calibration method used in the WSR-88D. A measurement uncertainty or variance is identified for each component from which a variance budget is compiled. The composite variance prescribes the "goodness" of the measurement, and individual contributions identify areas for improvement. This is a working paper in that results will change as work progresses. The results presented serve only to present the status at this time.

## 2. Theory of Antenna Gain Measurement Using Solar Flux

The rigor of antenna gain determination by solar flux measurement lies in the fixed relationship between antenna gain and antenna effective area. Antenna gain, g (unitless), is given by: [Silver, 1949]

$$g = \frac{4\pi A_e}{\lambda^2} \ \textit{it follows that} \ A_e = \frac{\lambda^2 g}{4\pi}$$

where

$$\lambda = \textit{radar wave length, meters}$$

$$A_e = \textit{antenna effective area, square meters}$$

$$\textit{Antenna effective area is given by:}$$

$$A_e = \eta A$$

$$A = \textit{antenna physical area, square meters}$$

$$\eta = \textit{aperture efficiency, unitless}$$

Aperture efficiency contains both ohmic losses and the effects of the primary illumination function. The mid band aperture efficiency for the WSR-88D is 0.589 and varies about $\pm$ 0.6% across the 2.7 GHz to 3 GHz band. Efficiency is inherent in range measured gain and is accounted for in derived gain versus frequency relationships. [Sirmans, 1992]

Solar flux can be used to estimate antenna gain by the following simplified steps:
The solar power received by the radar is given by:

$$Solar\ Power = \hat{P}r = F\ x\ BW_n\ x\ Ae$$

where

$$\hat{P}r \quad = received\ power, watts$$

$$F \quad = solar\ flux, watts / m^2 / Hz$$

$$BW_n = receiver\ noise\ bandwidth, Hz$$

$$Ae \quad = antenna\ effective\ area, m^2$$

Using the known solar flux and the relationship between gain and effective area, the antenna estimated gain is

$$g_E = \frac{4\pi}{\lambda^2}\left[\frac{\hat{P}r}{F\ x\ BW_n}\right]$$

Thus, if the solar flux density and radar noise bandwidth are known, the received power provides an estimate of antenna effective area which specifies antenna gain. The need to know the receiver noise bandwidth and noise power explicitly can be eliminated by use of a broadband noise source having the same spectral density characteristics as the solar flux, and if flux power is measured as a ratio of flux power to thermal noise power. This will be discussed in the description of the WSR-88D flux power measurement.

The antenna gain estimate can also be cast in terms of the sun brightness temperature. Solar flux is related to brightness temperature by: [Andrews, 1969] [Skolnik, 1970]

$$F = \frac{(1.88)(10^{-27})\,T}{\lambda^2}$$

where

$$F = flux\ density, watts / m^2 / Hz$$

$$T = brightness\ temperature,\ Kelvins$$

$$\lambda = radar\ wave\ length, meters$$

The typical sun brightness temperature at several radio frequencies is shown in Figure 1. Note that in general, brightness temperature (and solar flux) varies with both frequency and distance from center of solar disk. Although the brightness temperature decreases with frequency in general, the WSR-88D band is in a subregion where temperature increases with frequency.

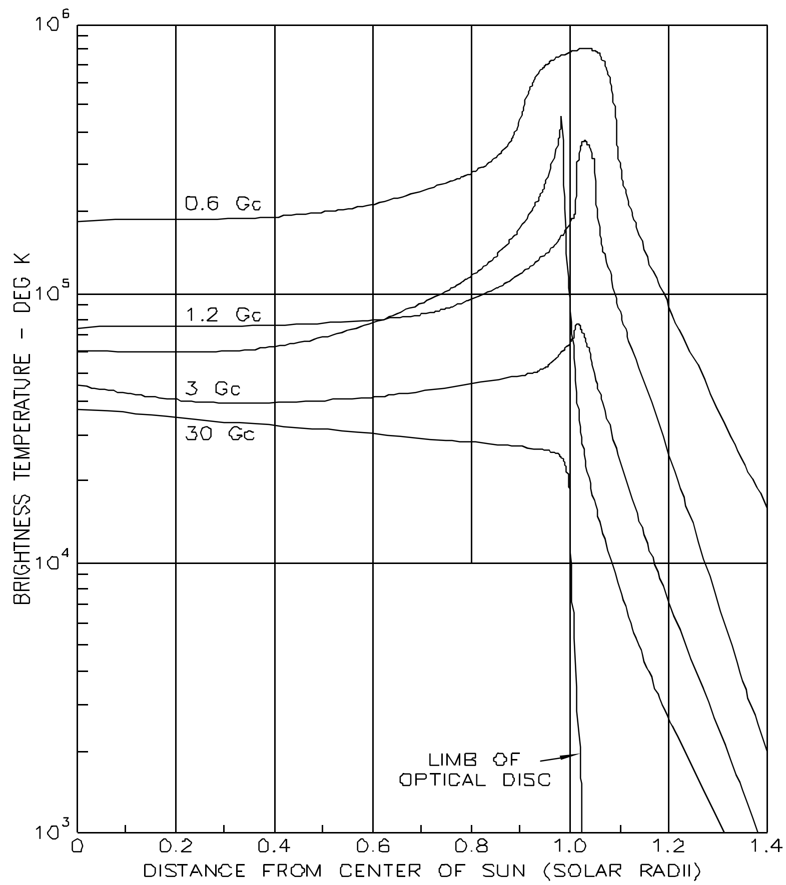


Figure 1. Sun Brightness Temperature at Various Frequencies. Note that the radio sun is larger than the optical sun. From Andrews, 1969

## 3. Characteristics of the Solar Flux

Important aspects of the solar flux for antenna gain measurement is the frequency and accuracy of the reported flux value. Accuracy and traceability of the flux varies widely with the research observatory performing measurements. For example, Sagamore Hill does not make an absolute measurement but does maintain consistency within their network [Robinson, April 2000]. Sites deviating from the mean network observation value by more than 10% are adjusted to agree. About once a decade the observations are compared to a known celestial source. The observational frequency closest to the WSR-88D band is at 2695 MHz. Ottawa, NRC has an accuracy of about 5% and observational frequency of 2800 MHz. Solar flux measurements most applicable to the WSR-88D antenna gain measurement are the Penticton observations (Dominion Radio Astrophysical Observatory, Penticton, B.C.) with absolute accuracy of 1% or 1 solar flux unit, whichever is larger, and observational frequency of 2800 MHz. [Tapping, April 2000]

The measurement accuracy of the observation is important since it plays a major role in determining the accuracy of the antenna gain measurement. The observation frequency is important since the flux density varies with frequency. For estimating sun flux at frequencies other than 2800 MHz, an extrapolation formula offered by Tapping [1994] is given by:

$$S_f = (\alpha S_{10} + \beta)\ (f - 2800) + S_{10}$$

where

$$S_f = \textit{flux density at the required frequency, solar flux units}$$
$$S_{10} = \textit{flux density at 2800 MHz, solar flux units}$$
$$f = \textit{frequency in MHz}$$
$$\alpha = 0.0002$$
$$\beta = -0.01$$

The relationship was established from a mixture of theory and empirical data and most of the time, has an error of only 2%. The product terms can be cast as the adjustment to the reported flux at 2800 MHz necessary to obtain the flux at the observed difference frequency. This adjustment is plotted in Figure 2 for the WSR-88D frequency band.

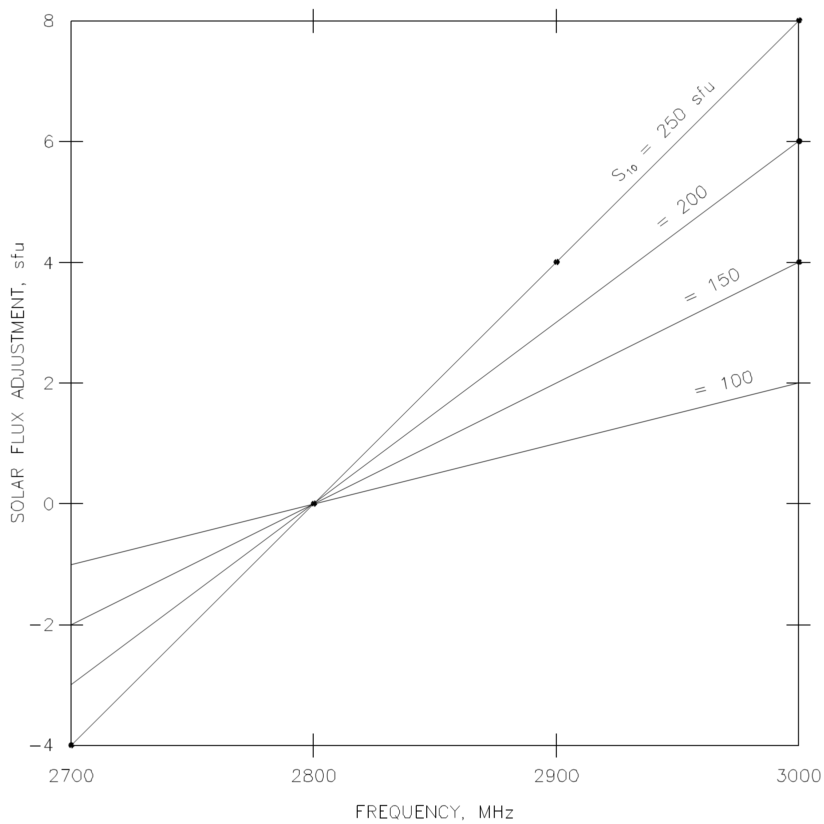


Figure 2. 2800 MHz Solar Flux ($S_{10}$) Adjustment for Estimating Solar Flux Across the WSR-88D Frequency Band. After Tapping, 1994

Sun flux has a temporal variation with a nominal period of 27 days synchronous with solar rotation [Pratt, 1995]. ( The sun also has a temporal variation over an eleven year period associated with sunspot activity.) An example of the magnitude and periodicity of the rotational temporal variation is illustrated in Figure 3. The daily variation in flux is important in WSR-88D antenna gain measurement since simultaneous radar and observatory measurements cannot be easily done with the RDASOT Sun Check routine. Flux density daily temporal gradient during periods of rapid change is about 2 sfu per hour corresponding to about 0.04 dB/hr at present flux values.

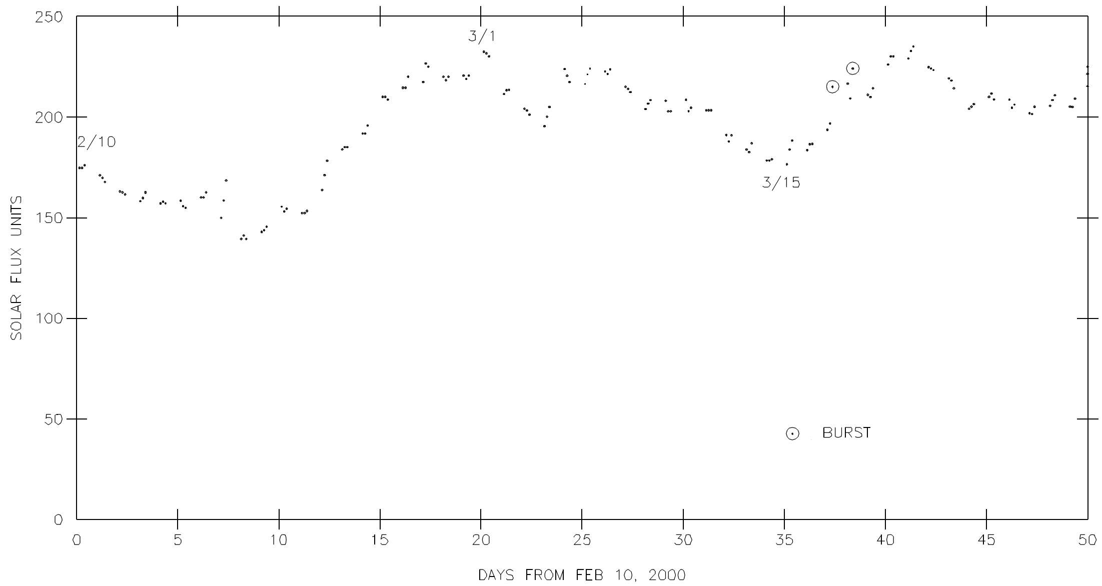


Figure 3. Solar Flux Density Rotational and Daily Variation. Flux gradient due to sun rotation is about 15 sfu/day and daily gradient is about 2 sfu/hour.

Utilization of the solar flux observatory measurement in the radar antenna gain measurement requires knowledge of the reported flux data series. The Penticton Observatory reports three values: The "Series C, Observed Flux Density" is the actual measured value of the radio flux incident upon the earth. "Series C, Adjusted Flux Density" is the flux density adjusted to an earth-sun distance of one Astronomical Unit (the average earth-sun distance). "Series D" is the URSI Commission V suggested best estimates of the absolute flux density obtained by multiplying the "Observed" or "Adjusted" values by 0.9. All values are given in solar flux units of $10^{-22}$ watts /meter$^2$/ Hertz. All observations are solar flux measurements at all polarizations and must be reduced by a factor of two for comparison with the single polarization measurement of the WSR-88D. This correction is referred to as the polarization constant of value 2 in WSR-88D software documentation.

The "Series C, Adjusted Flux Density" is the observation most suitable for comparison with the WSR-88D measurement since the calculated sun temperature in the WSR-88D antenna gain measurement routine contains an earth sun distance correction.

The daily schedules of the Penticton observations vary with the time of year due to the latitude of the observatory and its location in a mountain valley. From November through February the observations are at 1800, 2000, 2200 Universal Time (UT) . From March through October the observations are at 1700, 2000, and 2300 UT. Solar flux density temporal variation influence on antenna gain estimation can be minimized by making the WSR-88D measurement near these observatory observation times.

The Penticton Observatory is in British Columbia near the U.S. border about midway between Spokane and Seattle. For sites east of the Mississippi River, observation at early to late afternoon reduce the temporal variation. For sites west of the Mississippi River, noon to early afternoon observations reduce the temporal variation. As will be seen from the variance analysis, it is not critical that the gain check be made at the same time as the observation. However, it is critical that the gain check be done during the observatory period for monitoring solar bursts so that gain measurements made during bursts can be recognized.

As can be inferred from Figure 1, the radio sun observed at a centimeter or longer wavelength is larger than the optical sun. At an observational wavelength of 10 cm, the radio sun is about 7% larger than the optical sun. The optical sun disk subtends 0.525 degrees to 0.542 degrees over the year due to earth orbital eccentricity, so the 10 cm radio sun subtends 0.5618 to 0.5799 degrees.

The WSR-88D Sun Check software calculation requires a beamwidth correction for comparison with the observation. Since the radio sun (0.56 to 0.58 degrees) subtends an appreciable fraction of the 3 dB antenna beamwidth (0.88 to 0.96 degrees), the radar measurement is a weighted average, not the peak value reported by the observatory. (Penticton antenna beamwidth is 5 degrees and no correction for beamwidth is made.) The beamwidth correction is derived by averaging the product of antenna pattern and solar radiation over the angle subtended by the solar disk. Beamwidth correction factor, k, is given as: [CPC 06, 3.10.6.1.2]

$$k = \left[1 + 0.18\left(\frac{\theta_s}{\theta_3}\right)^2\right]^2$$

where

$$\theta_s = \textit{angle subtended by optic sun, degrees}$$

$$\theta_3 = \textit{antenna 3dB beamwidth, degrees}$$

Antenna beamwidth correction given by the above formula is shown in Figure 4. The mean correction factor corresponding to the average solar disk angle of 0.5708 degrees ranges from 1.131 to 1.157 across the WSR-88D frequency band. The frequency dependent mean correction of 0.535 dB to 0.633 dB has a sun distance uncertainty of about ± .02 dB. The WSR-88D beamwidth correction routine uses the optical sun angle. This results in an underestimate of the correction factor by 0.08 dB.

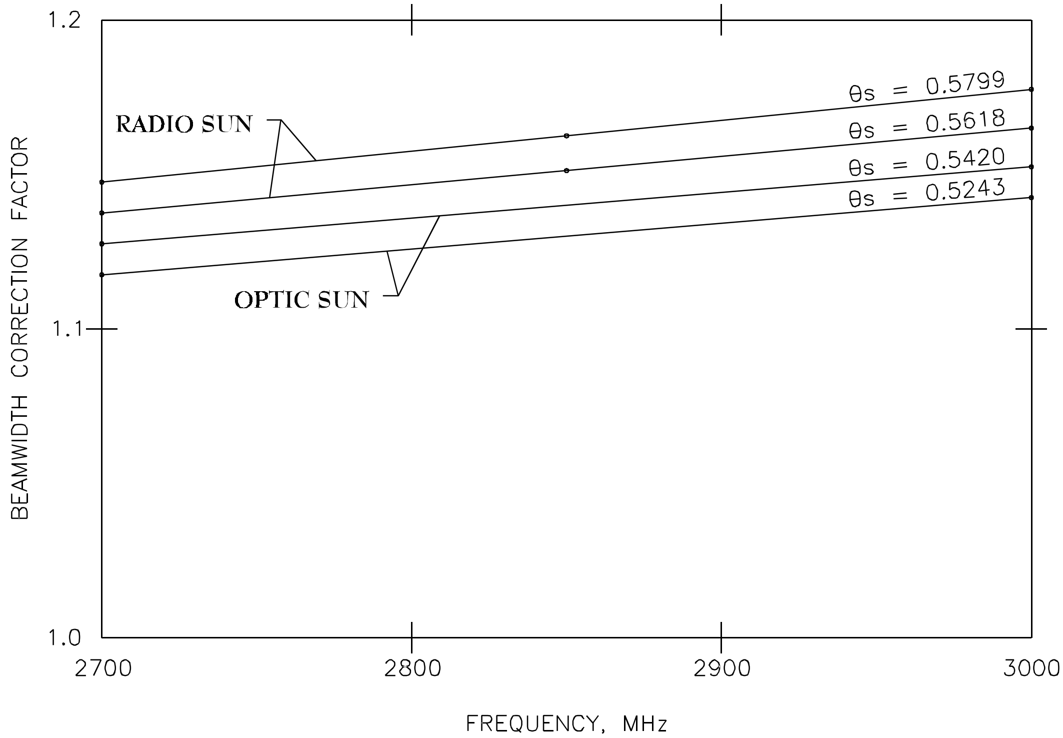


Figure 4. Calculated Sun Flux Correction for Antenna Beamwidth of the WSR-88D. Corrections for the maximum and minimum optic and radio sun subtended angles are shown.

## 4. Description of the WSR-88 Solar Flux Measurement Routines

The solar flux measurement routine is described in Specification Number 1208265, paragraph 3/10.6, CPC 06, A606, Sun Check Calibration. The module is divided into two sub-tests. Sub-test 1 performs pedestal alignment and antenna beamwidth check functions. Sub-test 2 performs the antenna gain/radome and microwave loss check function. However, the bulk of radar calibration is done in Sub-test 1 which should always be run at least once before Sub-test 2.

The antenna gain/radome /microwave loss composite is expressed in terms of the sun noise temperature. A sun noise temperature is computed from the observatory reported flux value and composite antenna gain listed in the Receiver adaptation data. The sun noise temperature is then measured using the radar self calibration routines and internal noise source. The two noise temperatures (calculated and measured) are compared to create an antenna gain adjustment which can be accepted by the operator. At the operator's discretion, the antenna gain adaptation data parameter can be changed to compensate for the antenna gain adjustment.

Sun noise temperature is calculated in two steps corresponding to an uncorrected and corrected value, corrections being for the characteristics of the specific radar. Uncorrected computed sun temperature, $T_u, (Kelvin)$ is given by [3.10.6.1.2 of CPC 06, A606]

$$T_u = \frac{g \;\; \lambda^2 \;\; sfu\left(10^{-22}\right)}{4\pi\, 2 \;\; B}$$

where

g = antenna gain, dimensionless = $10^{\frac{G}{10}}$

G = antenna gain, dB

$$\lambda = radar\ wavelength, m = \frac{299735000}{f}$$

*f = radar frequency, Hz*

$\dfrac{sfu\left(10^{-22}\right)}{2}$ = Observatory reported solar flux units, sfu, adjusted for single polarization, ½ , and converted to power, $10^{-22}$ watts/m$^2$/Hz

B = Boltzmann's constant = 1.3806 ($10^{-23}$) watt - sec/K

Three corrections are made to this initial calculation. As discussed in section 2 if the sun subtends an appreciable portion of the antenna beamwidth, the measured solar flux will be underestimated due to off-axis antenna gain. The calculated temperature is corrected for beamwidth per [3.10.6.1.2]

As mentioned, an earth-sun actual distance correction is made [3.10.6.1.3.2] which requires the observatory "Series C, Adjusted Flux Density" which has been adjusted to the average earth-sun mean distance be used in the calculation. The earth's orbital eccentricity is 0.0167 and the earth-sun distance varies about its mean by ± 0.835%. The distance correction enters the temperature estimation in the calculation of the optical sun diameter used in the beamwidth correction as a linear distance factor, $DC^{1/2}$ (unitless). In the adjustment of calculated flux, the earth-sun mean distance enters as a distance-squared factor, $\frac{1}{DC}$ .

The predicted temperature is also adjusted for translation to the point of reference for the measured temperature. The point of reference for the WSR-88D is the input to the receiver protector, 2A3J1. Thus the predicted sun temperature is reduced by the receiver microwave loss, RML, from antenna port to receiver input. The adjustment factor, α, is given by:

$$\alpha = 10^{\frac{RML}{10}}$$

where

RML = receiver microwave loss, dB. This is by WSR-88D convention a negative number.

Predicted noise temperature is then given by:

$$T_C = \frac{g\;\lambda^2\;sfu\left(10^{-22}\right)}{4\pi \quad 2 \qquad B} \quad \frac{10^{\frac{RML}{10}}}{\left[1 + 0.18\left(\frac{\theta_S}{\theta_3}\right)^2\right]^2} \quad \frac{1}{DC}$$

The sun noise temperature is measured in two steps using the internal noise source. The noise generator is a broadband source having essentially the same spectral characteristics as the radio sun. Use of a broadband source of known spectral density eliminates the need to know the receiver noise bandwidth and receiver noise power. Background or "blue sky" noise temperature is measured with the antenna pointed 3 degrees away from the sun. Sun noise temperature is measured with the antenna pointed directly at the sun. The background temperature is subtracted from the direct temperature to produce the sun temperature. (The authors have some reservation with this approach since it assumes no sun blockage of blue sky radiation; however, this has a minimal effect.)

Actual measurement consists of four radials containing two sets of noise data. One set is with the noise source off and another set with the noise source on. The excess noise ratio, ENR, at the reference point is given by:

$$ENR = 10^{\frac{(Ts\_noise + Path\ loss)}{10}}$$

where

Ts_Noise = output level of the RF Noise Source in dB, a positive number

Path loss = total loss from noise source output port to point of reference, dB. This loss is a negative number.

Blue sky and direct sun noise temperatures are related by the system noise equation:

$$T_m = \frac{290\ Kelvins\ \ ENR}{\left[\dfrac{noise\ with\ noise\ source\ on}{noise\ with\ noise\ source\ off} - 1\right]}$$

Measured sun noise temperature is given by the difference

$$T_m = T_{direct} - T_{bluesky}$$

The ratio of measured sun temperature to calculated sun temperature is taken as the gain discrepancy where

$$\Delta G = 10 \log \frac{T_m}{T_c}$$

This delta value is referred to as Gain Adjustment in RDASOT Sun Check display. The recommended new Antenna Gain (A1 in Antenna Adaptation data) is referred to as Adjusted System Gain Estimate. Both quantities are in dB.

5. Noise Source and Receiver Calibration

The WSR-88D receiver channel is a conventional S-band radar receiver consisting of a Low Noise Amplifier near the 28 feet parabolic antenna, a Mixer/Preamp which produces an IF of 57 MHz, a Matched Bandpass filter, an instantaneous AGC switched attenuator which attenuates medium to large signals, an IF amplifier limiter with a gain of 40dB, an I/Q Phase Detector followed by individual Analog to Digital Converters for the I and Q video. A special feature of the A/D converters is a digital to analog feedback loop which reduces DC Offsets on the two A/D outputs down below one LSB of the A/D converters. This occurs automatically every Volume Scan. The resultant noise data which is free from DC offsets is used in the reflectivity calculation to enhance reflectivity accuracy.

The gain of the amplifier limiter is adjustable and is set so that two LSB's of the A/D converters are toggling on receiver set noise plus "blue sky" noise, ie., the antenna is pointed away from the sun and the earth which are thermally “hotter” than the blue sky. The amount of power measured under these circumstances is the System Noise Temperature, an important indicator of receiver sensitivity and minimum discernible signal. The System Noise Temperature is measured and monitored every volume scan in the Operate mode. An increase in System Noise Temperature is indicative of reduced receiver sensitivity.

System Noise Temperature (Receiver Noise) is computed by taking two noise power measurements as stated in the previous section, one a “blue sky” measurement and the other with the internal wide band noise source turned on so that the measurement is actually the blue sky noise PLUS the internal noise. If the internal noise source is accurately known, the System Noise Temp can be accurately calculated from the two resultant power measurements. The internal noise source is located in the equipment shelter, up to 30 meters removed from the reference point 2A3J1 of the Receiver Protector. Until recently, we have had to rely on the calibration sticker value of the internal noise source even though experience over the years had made this data highly suspect. We recently purchased a Noise Standard which in combination with tight controls on the path losses, between the Noise Source and the reference point, has given us more reliable System Noise Temperature data.

Solar Flux Measurements are performed by the Sun check routine of RDASOT, an off line diagnostic and calibrating program, which consists of the following two subtests:

Subtest 1 Align Pedestal
The position of the sun is calculated from the Lat Long of the site in adaptation data and the correct Universal Time inputted by the operator. The WSR-88D antenna scans plus and minus three degrees in Azimuth while measuring the noise output of the receiver channel. The azimuth of maximum power is defined as the sun azimuth. The antenna then scans plus and minus three degrees in elevation. The elevation of maximum power is defined as the sun elevation. Any differences between the initially calculated sun position and the experimentally determined position form the basis of a long-term azimuth and elevation correction. The operator is given the option of accepting the correction or not by the software routine. If the corrections are too large, aligning of the azimuth and/or elevation shaft encoders may be in order. Performance of subtest 1 is a pre-requisite for performance of subtest 2 wherein the sun is tracked while the sun noise power is measured. Accurate positioning of the antenna is obviously essential for this to be successful.

Subtest 2 Gain/Loss Check
This subtest checks the Antenna Gain/Radome loss by computing the predicted sun noise temperature from solar lab data and the measured sun noise temperature. Correction of adaptation data parameter A1 Antenna gain is then suggested based upon the ratio of the two sun noise temperatures.

The Sun Noise Temperature is measured in an almost identical manner as the System Noise Temperature, the difference being that the antenna is made to point directly at the sun during the two measurements ie., one with the internal noise source off, the other with the noise source on. An independent absolute solar flux measurement is made routinely by Solar Laboratories such as Penticton in Canada. The latest solar flux from Penticton is ascertained and input by the operator when prompted by the software routine. In addition to the flux, the correct Universal Time is also input by the operator.

Since the accuracy of the sun noise temperature is directly dependent upon the proper calibration of the Internal Noise Source, the capability of this subtest has not been used to calibrate Antenna Gain prior to release of Change 6 of the RDA Maintenance manual because of the lack of a good method of calibrating the internal noise source. Change 6, which introduces use of the newly purchased Noise Standard, now permits use of the capability of Subtest 2 to calibrate Antenna Gain.

Figure 5 is a plot of the results of calibrating the antenna using the new procedures at several field sites. The line labeled “Adaptation Data per Andrew’s formula” is the value of antenna gain used prior to the calibration based upon data taken several years ago by the antenna vendor, Andrews. This is the value used by all sites prior to using the new procedure. The X’s represent values of antenna gain obtained by using the new calibration procedures. Those falling below the Andrews line would cause an under estimate of precipitation while those falling above would cause an overestimate. Note that the majority of sites calibrated exhibited calibration errors in a direction to cause under estimates (ie., lower than predicted antenna gain) while a few sites are very close to or above predicted values. No specific cause of the general lower gain have been identified to date. Note also that the reflectivity error due to antenna gain errors is TWICE the value indicated on the Figure since antenna gain is squared in the reflectivity equation. Generally speaking, a 1dB error in antenna gain causes a 2dB error in reflectivity which causes an approximate 36% error in rainfall accumulation.

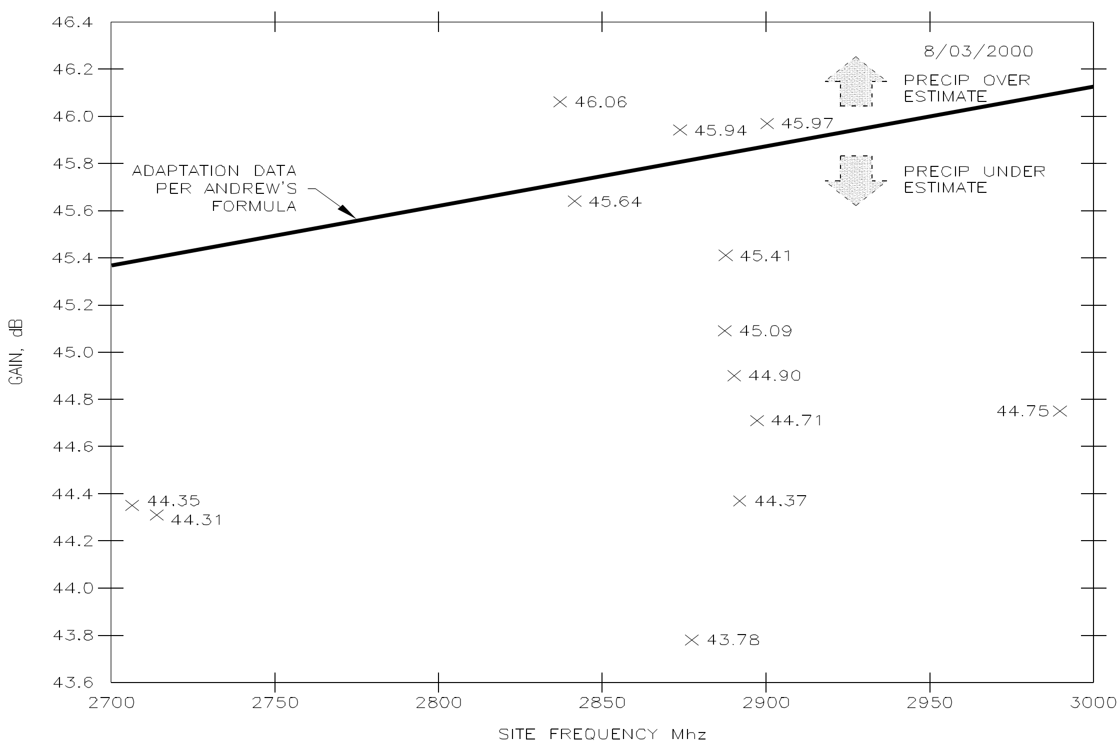


Figure 5. Comparison of Sun Flux Results with Adaptation Data Values.

The process portions of the antenna gain variance budget is shown in Table 1. There are two columns listed: the estimated Outer Bound and the estimated Standard Deviation across the population of field sites. The paragraphs following the table explain the details of the listed process.

Table 1
Antenna Gain Variance Budget

| PROCESS | ESTIMATED OUTER BOUND dB | ESTIMATED STANDARD DEVIATION dB |
|---|---|---|
| Calibration of Noise Standard | 0.30 | 0.05 |
| Calibration of Noise Source | 0.20 | 0.20 |
| Calibration of PL up to 4J16 | 0.20 | 0.10 |
| Cal PL 4J16 to 4J15 | 0.20 | 0.10 |
| Cal of Antenna Gain | 0.10 | 0.10 |
| Cal Chk after initial cal | 0.30 | Insufficient data |

Calibration of the Noise Standard is the dominant uncertainty. As stated previously, the absolute accuracy traceable to NIST standard of any particular Noise Standard is +/- 0.3dB. The Engineering prototype was used to calibrate the Springfield, MO field site with excellent results as shown in Figure 6. The WSR-88D at Springfield had consistently under estimated rainfall with respect to rain gauges in the area as seen from the “uncalibrated” data in Figure 6. After calibration using the Change 6 procedures in conjunction with the Engineering prototype Noise Standard, the improvement in agreement between the Radar and rain gauges is striking.

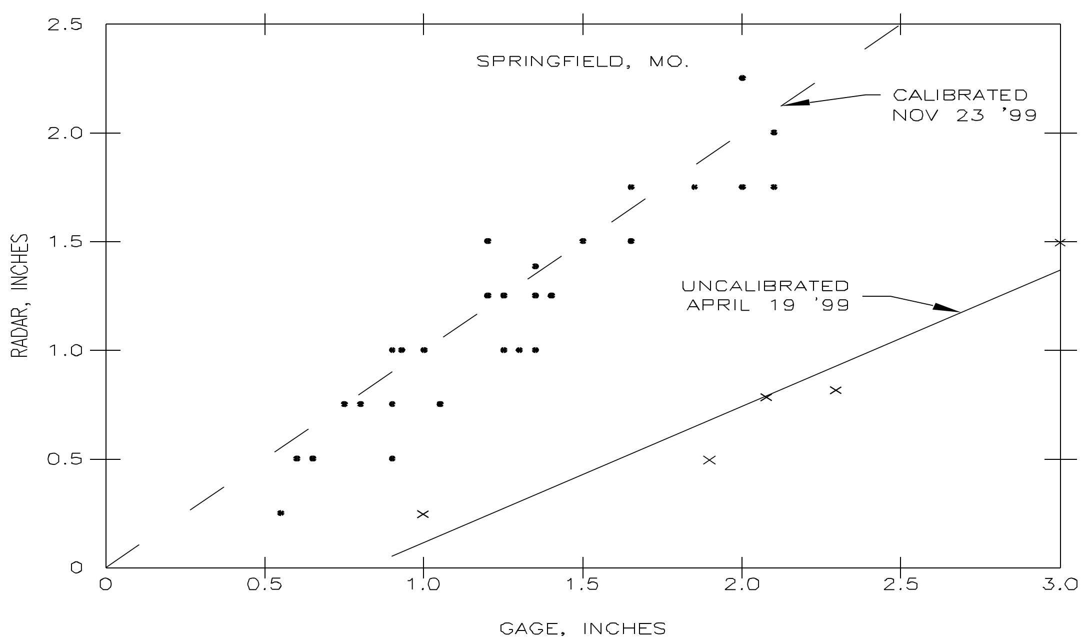


Figure 6. Gauge rainfall and radar rainfall comparison before and after radar calibration with Engineering Prototype Noise Source.

Based upon these results, 19 additional Noise Standards were purchased. In an effort to calibrate the additional units to the Engineering prototype more precisely than +/- 0.3dB, a method of accomplishing this to an accuracy of +/-0.05dB was developed. Table 2 is a listing of the results of this additional calibration to the Engineering prototype which is considered a Primary standard based upon its success at Springfield.

Table 2
Noise Standard Calibration Data

| Serial Number | Offset* (dB) | $P_{wb}$ (dBm) |
|---|---|---|
| 5000 (1st Article) | +0.31 | -17.04 |
| 5001 | -0.14 | -17.84 |
| 5002 | -0.19 | -17.73 |
| 5003 | -0.12 | -17.69 |
| 5004 | -0.15 | -17.55 |
| 5005 | .00 | -17.72 |
| 5006 | -0.03 | -17.36 |
| 5007 | -0.25 | -17.38 |
| 5008 | .00 | -17.94 |
| 5009 | .00 | -17.59 |
| 6845 (NRC Standard) | -0.48 | -15.15 |
| Serial Number | Offset (dB) | $P_{wb}$ (dBm) |
| 5010 | -0.50 | -17.90 |
| 5011 | -0.45 | -17.52 |
| 5012 | -0.45 | -17.54 |
| 5013 | -0.25 | -17.43 |
| 5014 | Reject | |
| 5015 | -0.20 | -17.78 |
| 5016 | -0.35 | -17.65 |
| 5017 | -0.22 | -17.56 |
| 5018 | -0.25 | -17.40 |

Note from Table 2 that the offsets from the Engineering Primary Standard are consistent with the published absolute accuracy of +/- 0.3dB and that the values of the offsets are consistent with resolution of differences from the Primary Standard within an accuracy of +/- 0.05dB.

Use of one of the Secondary Noise Standards in calibrating the Internal Noise Source 4A25 is imperative for reliably calibrating the antenna gain using the Sun Check Subtest 2. This calibration is accomplished by substituting the Noise Standard for the Internal Noise Source and properly setting R35, the adaptation data which states the Excess Noise Ratio (ENR) of the combination of the Noise Standard and a test cable supplied with the standard. The WSR-88D system is then allowed to perform the System Noise Temp routine until a calibrated System Noise Temp is established with the Noise Standard in place. When this is complete, the Internal Noise Standard is disconnected and the Internal Noise Source is reconnected normally. R35 is then adjusted until the calibrated System Noise Temp is displayed to an accuracy equivalent to +/- 0.2dB. This completes the calibration of the Internal Noise Source 4A25. Note that this part of the overall calibration is impervious to path loss errors - we are simply comparing the Internal Noise Source to the Noise Standard.

Calibration of the path losses from the Internal Noise Source 4A25 to the reference point 2A3J1 is accomplished in three steps as follows:

* Calibration of the path from the RF Frequency Generator up to 4J16.
    - Calibration of this path is checked to an accuracy of +/- 0.20dB by comparing a power measurement using a HP 436A power meter with the sum of adaptation data up to this point. If the measurement does not agree with the expected value, i.e., the sum of adaptation data losses, remedial action is required to properly correct adaptation data.

* Calibration of the path from 4J16 through the Antenna Pedestal and back down to 4J15.
    - Calibration of this path is checked to an accuracy of +/- 0.20dB by comparing the two measurements at 4J15 and 4J16 with the sum of appropriate adaptation data. Again, if the tolerance is exceeded, remedial action is required.

* Calibration of the path from the Noise Source through the 4 position switch. This path loss is checked to an accuracy of +/- 0.05dB.

When the Internal Noise Source and path losses are properly calibrated, Sun Check Subtest 2 may be used to calibrate the antenna gain. The latest solar flux for the Penticton solar lab must be obtained (it is available on the internet www.sec.noaa.gov). In addition, the correct Universal Time available at (303)499-7111 must be used.

Experience with Sun Check sub-test 2 has revealed that the readout Gain Adjustment has a standard deviation of approximately 0.2dB. For this reason, the routine is run five times and the average is used to correct the antenna gain.

After the initial calibration is accomplished, a 28 day P.I. should be established to assure that errors in gain adjustment in excess of +/-0.3dB result in remedial action. Note that the Sun Check Subtest 2 is sensitive to changes in calibration of the Internal Noise Source, the path losses involved as well as changes in antenna gain. It is likely that there will not be any changes in antenna gain after the initial calibration, but changes in the other parameters is possible.

To date, the controlled check of process stability at Springfield indicate that the subtest 2 Gain Adjustment can be expected to stay within the required accuracy for at least two years. This figure may be revised as more data is collected.

6. Antenna Gain Estimate Variance Budget

As noted in the previous sections, the antenna gain adjustment consists of calculating the difference between measured sun temperature and calculated sun temperature using an assumed gain (adaptable parameter value).

The uncertainty associated with the difference is, of course, proportional to the uncertainties associated with the two quantities. Cast in logarithmic form, the expression for the variance reduces to that of a linear arithmetic operation [Burington and May, 1953] given by

$$\sigma_\Delta^2 = \sigma_m^2 + \sigma_c^2 - \rho\,\sigma_m \sigma_c$$

where

$$\sigma_\Delta^2 = \mathrm{var}\,iance\ of\ gain\ difference$$

$$\sigma_m^2 = \mathrm{var}\,iance\ of\ measured\ temperature$$

$$\sigma_c^2 = \mathrm{var}\,iance\ of\ calculated\ temperature$$

$$\rho = correlation\ of\ measured\ and\ calculated\ temperatures$$

Calculated and measured temperature have no common elements; thus, ρ = 0 and the difference variance is the sum of individual variances.

The Sun Temperature is calculated by

$$10\log T_c = 10\log g + 10\log \lambda^2 + 10\log sfu + 10\log\frac{10^{-22}}{8\pi B} - RML$$

$$-10\log\left[1+0.18\left(\frac{\theta_S}{\theta_3}\right)^2\right]^2 - 10\log DC$$

Sun Temperature is measured by

$$10\log T_m = 10\log 290\,Kelvins + 10\log ENR - 10\log\left[\frac{noise\ source\ on}{noise\ source\ off} - 1\right]$$

and the Gain Differential is given by

$$\Delta G = 10\log T_c - 10\log T_m$$

The uncertainty associated with the individual terms can be assigned from the following considerations.

| | |
|---|---|
| 10 log g | - is the assigned gain, uncertainty is zero. |
| 20 log λ | - the radar frequency or wavelength is known to one part in $10^{-5}$, uncertainty is 0.000087 dB |
| 10 log sfu | - the solar flux is accurate to 1% or 1 sfu whichever is larger; for flux values greater than 100 sfu, the extrapolation uncertainty is less than 0.01 sfu; overall uncertainty is 0.044 dB. |
| $10\log\frac{10^{-22}}{8\pi B}$ | - is a constant, uncertainty is zero. |
| RML | - microwave loss is measured with uncertainty of about 0.1 dB. |

$$10\log\left[1+0.18\left(\frac{\theta_s}{\theta_3}\right)^2\right]^2 -$$

beamwidth correction contains two uncertainties and a bias. No references are given for the model. Thus, the assumptions and approximations used in the derivation are not known. However, comparison of results from this model with results from a Gaussian model with uniform solar disk and a manual integration of the actual solar disk (Figure 1) indicate an accuracy of about 0.1 dB. There is also an uncertainty in the overall correction due to the uncertainty of antenna beamwidth of 0.015 degrees. This translates to correction uncertainty of 0.023 dB. Total uncertainty is 0.103 dB. Since the radio sun is about 7% larger than the optical sun, use of the optical sun in the 88D routine results in underestimate of the correction factor by about 0.088 dB.

10 log DC - the earth sun distance is a robust calculation using Greenwich Sidereal Time (GST) and astronomy data. Two factors are calculated; (1.) The ratio of the sun's optical angular diameter to the sun's mean optical angular diameter, $DC^{1/2}$, is used to adjust the sun subtended angle in the beamwidth correction calculation and (2.) The reciprocal of this ratio squared, (DC), is used to adjust observed flux to a distance of one astrological unit. Calculations are done with double precision and for our purposes, we assume negligible uncertainty i.e., uncertainty less than 0.001 dB.

10 log 290 Kelvins - is a constant, uncertainty is zero.

$$10\log\left(\frac{noise\ on}{noise\ off}-1\right)$$

- The uncertainty of this term contains three factors; short term variability of sun flux, variance of the calculation, and sun boresight repeatability. Composite uncertainty is estimated from consecutive measurements, the standard deviation of thirty measurements from three sites is 0.11 dB.

10 log ENR - noise source calibration, uncertainty is 0.3 dB [Nichols, April, 2000]

Besides the terms in the calculated and measured noise temperatures, there are other factors which contribute to the uncertainty of the measurement. Among these are the temporal variation of the solar flux between radar measurement and the observatory measurement, radar measurement during a burst, and deviation from sun boresight in the radar measurement of sun location.

The temporal variations of sun flux is about 1% per hour during periods of rapid change (excluding bursts). If the radar measurement is made within two hours of the observatory measurement, the uncertainty is about 0.088 dB. (This time interval will be part of the recommended procedure.)

The effect of solar spectrum deviation from thermal [Tapping, 1994] on the gain estimate is unknown at this time. If significant deviations are confined to solar burst activity [Guidice, 1976] [Straka, 1977], the effects will be small. An effort will be made to avoid gain measurements during solar bursts

Solar burst activity will be handled as a data quality problem rather than as a variance in the measurement. Significant bursts or burst increases by more than 10% of the monthly mean occur some five to thirty times a month with durations of five minutes to two hours. The bursts are summarized in the Dominion Radio Astrophysical Observatory Monthly Solar Activity Report. It is recommended the radar measurement be compared with the solar burst summary for possible burst contamination.

Variance of the estimate due to uncertainty in sun boresight consists of two parts; uncertainty in sun location determination and uncertainty in antenna position using the boresight position command. Sun location is determined in RDASOT Sun Check Subtest 1. Flux data is acquired in a rasper mode over an area centered on the sun position calculated from almanac tabulation. Then the flux data is modeled as a parabolic relative to antenna azimuth and elevation with apex at the sun position. The uncertainty in sun location is given by the difference in variance of consecutive noise temperature measurements with both Subtest 1 and Subtest 2.

Boresight repeatability is one least significant bit of the encoder position which is 0.0439 degrees. Estimate uncertainty with a boresight error of 0.044 degrees is 0.033 dB. The boresight repeatability is part of the composite uncertainty estimated from Subtest 2 consecutive measurements of sun noise temperature.

Uncertainty associated with individual factors is tabulated in Table 1. Thus, if the individual uncertainties are treated as standard deviations, the composite standard deviation is 0.44 dB. This is conservative and most likely is an overestimate of the actual standard deviation since most of the individual specifications are bounds rather than standard deviations of some probability density. For example, accuracy of the dominate term 10 log ENR is specified as ± 0.16 to ± 0.30 dB and probably does not exceed ± 0.30 dB with significant probability. If the ENR uncertainty is uniform over this interval, the expectation is ± 0.23 dB, the standard deviation is 0.133 dB, and the composite standard deviation is 0.25 dB. If the uniform over the interval is ± 0.3 dB, the ENR standard deviation is 0.173 dB and composite standard deviation is 0.27 dB. In practice the standard deviation of the gain measurement will be closer to 0.35 dB than to 0.44 dB.

Table 1
Uncertainty Budget

| Term | Uncertainty, dB |
|---|---|
| 10 log g | 0 |
| 20 log λ | 0.000087 |
| 10 log sfu | 0.043 |
| $10\log\frac{10^{-22}}{8\pi B}$ | 0 |
| RML | 0.1 |
| $10\log\left[1+0.18\left(\frac{\theta_s}{\theta_3}\right)^2\right]^2$ | 0.111 |
| 10 log DC | 0.001 |
| 10 log 290 Kelvins | 0 |
| 10 log ENR | 0.3 |
| $10\log\left[\frac{noise\ on}{noise\ off}-1\right]$ | 0.11 |
| Temporal change in flux between observatory and radar measurement | 0.08 |
| Sun position determination | 0.044 |
| Calibration of noise source | 0.2 |
| Calibration of path loss | 0.14 |
| Deviation of solar flux spectrum from thermal | 0 |
| Total measurement and process variance | $\Sigma\sigma^2 = 0.194\ dB^2$ |
| Standard deviation | $\sigma = 0.44\ dB$ |

## 7. Summary

Examination of the various factors involved indicates that the WSR-88D Antenna Gain, Radome loss and received signal microwave loss can be estimated by the Sun Check routine built into each of the WSR-88D systems to an accuracy of 0.44dB. This figure applies as an absolute accuracy for any particular field site and considered as the standard deviation across the entire population of 180 odd field sites. Although an antenna accuracy gain of 0.2 dB is attainable on a carefully controlled and instrumented radar range, the gain measured by the Solar Flux method has the advantage of using solar energy coupled to the receiver calibration port, being traceable to an absolute standard and is verifiable without use of unrepeatable historical data. Another obvious advantage is that the required hardware and software is already deployed in the field. The additional SERD item, the Noise Standard, is also available for field deployment at this time.

Another extremely useful characteristic of using the sun as a test signal source is that since the same sun is available to all field sites, this technique is a vital element of overall WSR-88D network calibration monitoring. Present tech manual procedures require performance of the Sun Check solar flux measurement as a 28 day P.I.

In terms of accuracy of hydrological products, such as rainfall rate, the solar flux accuracy of 0.44dB is equivalent to a rainfall rate accuracy of +/- 8 % assuming a Z/R relationship of $Z = 300\,R^{1.4}$

## 8. Recommendations

Maintenance Note 30 is the document which requires all field sites to implement the Noise and Solar calibration procedures. It is expected that this document will be distributed to the field sites around 1 October 2000. It is recommended that this Maintenance Note be expeditiously performed and that system performance be monitored to verify improved hydrological performance. In addition, on going engineering effort is required to verify process stability with a view for establishing adequate Noise Standard calibration intervals and to investigate anomalous performance, if any, at particular field sites.

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